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Asynchronous driving principle and its application to vibration control

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SUMMARY

The vibration control of megaframes with suspension systems is developed in this paper. The interaction between the megaframe and the suspension systems is first analysed, then asynchronous driving principle is proposed for vibration control of such structures. A numerical example is presented to show the application of asynchronous driving principle in the design of vibration control. The response of the megaframe with suspension systems under evolutionary random excitation indicates the feasibility and effectiveness of the proposed method. The vibration control method, though studied in a special case of the megaframe with suspension systems, is also applicable to the vibration control of combined structures with large secondary-to-primary mass ratio. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: asynchronous driving principle; vibration control; megaframe; suspension system

INTRODUCTION

Using suspension systems for vibration control was proposed several decades ago. The suspended boiler system is a successful application of such idea in industrial buildings. It was found that the suspended boiler systems did not suffer severe damage after earthquakes in Niigata and To-kachi_oki in Japan. In the Tangshan earthquake in China, whose intensity is 3° higher than that of seismic design in that region, the suspended boiler systems were still quite safe with only some local damage. Early in the year of 1927, Rasch proposed suspended building structures, in 1938 Willians suggested Megaframes With Suspension Systems (MFSS). Suspension systems have come into practical use in high rise building structures since late 1950s. A recent study shows that the response of the MFSS under earthquake can be decreased by 60–70 per cent than that of a traditional structural system [1].

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Another way to use the suspension systems is the tuned mass damper (TMD) or multiple tuned mass dampers (MTMD). It is proposed that the suspension systems can absorb the energy of the primary structure. It is generally agreed that the TMD is wind resistance, but there exist arguments on the effectiveness of TMD for earthquake resistance. Some studies show that TMD can really work in earthquake resistance [2, 3], while some others show it does not work at all [4, 5]. These contradictory results indicate that the effectiveness of the TMD in earthquake resistance depends on the parameters of the primary and secondary structures. This inspires a study on the interaction between the primary and secondary structures by changing the parameters of the structures [6]. The principle of TMD also inspires a mega subconfiguration as a way of vibration control in tall buildings [7], which proposed that the secondary structures in the tall building act as a kind of TMD or MTMD. A recent study [8] of MFSS shows that when the mass of the building is mainly concentrated on the secondary structures, it is unlikely that the secondary structures (suspension systems) will act as a kind of TMD. On the contrary, the combined system is mainly driven by the secondary structures and dominated by the dynamic behaviour of the secondary structures. Thus, some principles in the design of TMD and MTMD [9, 11] are not proper any more in designing such kind of combined primary–secondary structure.

In this paper, asynchronous driving principle is proposed to be a basic principle in the vibration control of MFSS. An illustrative example is given to show how it works. The study, though based on the MFSS, can be applied to some other combined primary–secondary structures, such as multi-tower structures with a large podium at the bottom.

EQUATION OF MOTION AND ANALYTICAL PROCEDURE

Consider an N-DOF of primary megaframe with N secondary suspension systems, each of which has s_i $(i = 1, 2 \ldots N)$ suspended floors, respectively. The equations of motion of the combined system can be expressed as follows:

$$\mathbf{M}_\mathrm{t}\ddot{\mathbf{u}}_\mathrm{t} + \mathbf{C}_\mathrm{t}\dot{\mathbf{u}}_\mathrm{t} + \mathbf{K}_\mathrm{t}\mathbf{u}_\mathrm{t} = -\mathbf{M}_\mathrm{t}\tau_\mathrm{t}\eta_\mathrm{g}(t) \tag{1}$$

in which $\eta_\mathrm{g}(t)$ is the ground acceleration input, τ_t is the influence coefficient vector, the dot over a variable denotes its time derivative, and $\mathbf{u}_\mathrm{t}$ is the total displacement vector (of order $n = N + \sum_{i=1}^{N} s_i$) defined as:

$$\mathbf{u}_\mathrm{t} = [\mathbf{y}_1^\mathrm{T}, \mathbf{y}_2^\mathrm{T}, \ldots, \mathbf{y}_N^\mathrm{T}, \mathbf{y}_p^\mathrm{T}]^\mathrm{T} \tag{2}$$

where $\mathbf{y}_p^\mathrm{T}$ and $\mathbf{y}_i^\mathrm{T} (i = 1, \ldots, N)$ are the displacement vectors with respect to the ground of the megaframe and the ith suspension system, respectively.

$$\mathbf{M}_\mathrm{t} = \begin{bmatrix} \mathbf{M}_1 & \mathbf{0} & \ldots & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{M}_2 & \ldots & \mathbf{0} & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \mathbf{0} & \mathbf{0} & \ldots & \mathbf{M}_N & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \ldots & \mathbf{0} & \mathbf{M}_p \end{bmatrix}, \quad \mathbf{K}_\mathrm{t} = \begin{bmatrix} \mathbf{K}_1 & \mathbf{0} & \ldots & \mathbf{0} & \mathbf{K}_{1p} \\ \mathbf{0} & \mathbf{K}_2 & \ldots & \mathbf{0} & \mathbf{K}_{2p} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \mathbf{0} & \mathbf{0} & \ldots & \mathbf{K}_N & \mathbf{K}_{Np} \\ \mathbf{K}_{1p}^\mathrm{T} & \mathbf{K}_{2p}^\mathrm{T} & \ldots & \mathbf{K}_{Np}^\mathrm{T} & \mathbf{K}_p + \sum_{i=1}^{N} \mathbf{K}_{0i} \end{bmatrix} \tag{3}$$

where $\mathbf{M}_i, \mathbf{K}_i$ $(i = 1, \dots, N)$, $\mathbf{M}_p, \mathbf{K}_p$ are the mass and stiffness matrices of the ith suspension system and megaframe fixed at their own basis (i.e. the megaframe fixed at the ground, the suspension systems fixed at the megaframe). $\mathbf{K}_{ip}$ $(i = 1, \dots, N)$ is the coupling matrix between the megaframe and the ith suspension systems. $\mathbf{K}_{0i}$ $(i = 1, \dots, N)$ represents the increment to the stiffness matrix of the megaframe due to the ith couple suspension system.

We apply a so-called admissible co-ordinate transformation [12] to Equation (1), in this way the so-called relative displacement vector is introduced.

$$\mathbf{u}_{\mathrm{r}} = [\mathbf{x}_1^{\mathrm{T}}, \mathbf{x}_2^{\mathrm{T}}, \dots, \mathbf{x}_N^{\mathrm{T}}, \mathbf{y}_p^{\mathrm{T}}]^{\mathrm{T}} \tag{4}$$

in which $\mathbf{x}_i = (i = 1, \dots, N)$ is the displacement of the vector of nodal points of the ith suspension system with respect to the connecting point. The relationship between the vectors $\mathbf{u}_{\mathrm{t}}$ and $\mathbf{u}_{\mathrm{r}}$ is

$$\mathbf{u}_{\mathrm{t}} = \begin{bmatrix} \mathbf{I}_1 & \mathbf{0} & \dots & \mathbf{0} & \mathbf{N}_{1p} \\ \mathbf{0} & \mathbf{I}_2 & \dots & \mathbf{0} & \mathbf{N}_{2p} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \mathbf{0} & \mathbf{0} & \dots & \mathbf{I}_N & \mathbf{N}_{Np} \\ \mathbf{0} & \mathbf{0} & \dots & \mathbf{0} & \mathbf{I}_p \end{bmatrix} \mathbf{u}_r \tag{5}$$

where $\mathbf{I}_i$ $(i = 1, \dots, N)$ and $\mathbf{I}_p$ is the identity matrix of order $(s_i \times s_i)$ and $(N \times N)$ respectively, N_{ip} $(i = 1, \dots, N)$ is the so-called pseudostatic influence matrix, given as

$$\mathbf{N}_{ip} = -\mathbf{K}_i^{-1}\mathbf{K}_{ip} \tag{6}$$

Because the suspension systems and megaframe is mono-connected, we have [12]:

$$\mathbf{K}_{0i} - \mathbf{K}_{ip}^{\mathrm{T}}\mathbf{K}_i^{-1}\mathbf{K}_{ip} = 0 \tag{7}$$

By means of the co-ordinate transformation defined in Equation (5), we obtain the equations of the combined system in term of relative displacement in the following form:

$$\mathbf{M}_{\mathrm{r}}\ddot{\mathbf{u}}_{\mathrm{r}} + \mathbf{C}_{\mathrm{r}}\dot{\mathbf{u}}_{\mathrm{r}} + \mathbf{K}_{\mathrm{r}}\mathbf{u}_{\mathrm{r}} = -\mathbf{M}_{\mathrm{r}}\tau_{\mathrm{r}}\eta_{\mathrm{g}}(t) \tag{8}$$

in which $\mathbf{M}_{\mathrm{r}}$, $\mathbf{C}_{\mathrm{r}}$, $\mathbf{K}_{\mathrm{r}}$, τ_{r} are the mass, damping, stiffness and influence coefficient matrices in the relative displacement co-ordination respectively.

We further reduce Equation (8) into a system of equations expressed in modal co-ordinates, according to the component-mode synthesis, the following co-ordinate transformation is defined:

$$\mathbf{u}_{\mathrm{r}} = \Gamma_{\mathrm{r}}\mathbf{q}, \quad \Gamma_{\mathrm{r}} = \begin{bmatrix} \Phi_1 & \mathbf{0} & \dots & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \Phi_2 & \dots & \mathbf{0} & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \mathbf{0} & \mathbf{0} & \dots & \Phi_N & \mathbf{0} \\ \mathbf{0} & \dots & \dots & \mathbf{0} & \Phi_p \end{bmatrix} \tag{9}$$

Φ_i $(i = 1, \ldots, N)$ and Φ_p are the modal matrices (of order $m_{si} \leqslant s_i$ and $m_p \leqslant N$) normalized with $\mathbf{M}_i$ $(i = 1, \ldots, N)$ and M_p, respectively, and obtained by solving the following eigenproblems:

$$\mathbf{M}_i\Phi_i\Omega_i^2 = \mathbf{K}_i\Phi_i \; (i = 1, \ldots, N), \quad \mathbf{M}_p\Phi_p\Omega_p^2 = \mathbf{K}_p\Phi_p \tag{10}$$

where $\Omega_i (i = 1, \ldots, N)$ and Ω_p are diagonal matrices listing the natural radian frequencies of the suspension systems and the megaframe, respectively.

Using the co-ordinate transformation defined in Equation (10), Equation (8) become a set of equations of order $m = m_p + \sum_{i=1}^{N} m_{s_i}$, generally smaller than the order of original system of the equations, which can be written as

$$\mathbf{M}_q\ddot{\mathbf{q}} + \mathbf{C}_q\dot{\mathbf{q}} + \mathbf{K}_q\mathbf{q} = -\mathbf{V}\eta_g(t) \tag{11}$$

$$\mathbf{M}_q = \begin{bmatrix} \mathbf{I}_1 & \mathbf{0} & \ldots & \mathbf{0} & \Phi_1^T\mathbf{M}_1\mathbf{N}_{1p}\Phi_p \\ \mathbf{0} & \mathbf{I}_2 & \ldots & \mathbf{0} & \Phi_2^T\mathbf{M}_2\mathbf{N}_{2p}\Phi_p \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \mathbf{0} & \mathbf{0} & \ldots & \mathbf{I}_N & \Phi_N^T\mathbf{M}_N\mathbf{N}_{Np}\Phi_N \\ \Phi_p^T\mathbf{N}_{1p}^T\mathbf{M}_1\Phi_1 & \Phi_p^T\mathbf{N}_{2p}^T\mathbf{M}_2\Phi_2 & \ldots & \Phi_p^T\mathbf{N}_{Np}^T\mathbf{M}_N\Phi_N & \mathbf{I}_p + \sum_{i=1}^{N}\Phi_p^T\mathbf{N}_{ip}^T\mathbf{M}_i\mathbf{N}_{ip}\Phi_p \end{bmatrix}$$

$$\mathbf{K}_q = \begin{bmatrix} \Omega_{s_1}^2 & \mathbf{0} & \ldots & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \Omega_{s_2}^2 & \ldots & \mathbf{0} & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \mathbf{0} & \mathbf{0} & \ldots & \Omega_{s_N}^2 & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \ldots & \mathbf{0} & \Omega_p^2 \end{bmatrix} \mathbf{C}_q = \begin{bmatrix} 2\xi\Omega_{s_1} & \mathbf{0} & \ldots & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & 2\xi\Omega_{s_2} & \ldots & \mathbf{0} & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \mathbf{0} & \mathbf{0} & \ldots & 2\xi\Omega_{s_N} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \ldots & \mathbf{0} & 2\xi\Omega_p \end{bmatrix}$$

$$\mathbf{V} = [\Phi_1^T\mathbf{M}_1 \;\; \Phi_2^T\mathbf{M}_2 \;\; \ldots \;\; \Phi_N^T\mathbf{M}_N \;\; \Phi_p^T\mathbf{M}_p + \textstyle\sum_{i=1}^{N}\Phi_p^T\mathbf{N}_{ip}^T\mathbf{M}_i]^T \tag{12}$$

ASYNCHRONOUS DRIVING PRINCIPLE

Suppose the excitation and the response in Equation (11) can be expressed as follows:

$$\eta_g(t) = P\mathrm{e}^{-\mathrm{j}\omega t}, \mathbf{q}(t) = P\mathbf{H}(\omega)\mathrm{e}^{-\mathrm{j}\omega t} \tag{13}$$

We can obtain the transfer functions in modal co-ordinates as follows:

$$\mathbf{H}_i(\omega) = [\upsilon_i + \omega^2\mu_i\mathbf{H}_p(\omega)]\cdot[\Omega_i^2 - \omega^2\mathbf{I}_i - 2\xi\omega\Omega_i j]^{-1} (i = 1, \ldots, N) \tag{14}$$

$$\mathbf{H}_p(\omega) = \left[\upsilon_p + \sum_{i=1}^{N}\mathbf{Z}_i(\omega)\upsilon_i\right]\cdot\left[\Omega_p^2 - \omega^2\mu_p - 2\xi\omega\Omega_p j - \omega^2\sum_{i=1}^{N}\mathbf{Z}_i(\omega)\mu_i\right]^{-1} \tag{15}$$

where

$$\mathbf{Z}_i(\omega) = \omega^2 \mu_i^{\mathrm{T}} [\Omega_i^2 - \omega^2 \mathbf{I}_i - 2\xi\omega\Omega_i j]^{-1} \tag{16a}$$

$$\mu_i = \Phi_i^{\mathrm{T}} \mathbf{M}_i \mathbf{N}_{ip}^{\mathrm{T}} \Phi_p \tag{16b}$$

$$\upsilon_i = \Phi_i^{\mathrm{T}} \mathbf{M}_i \tag{16c}$$

$$\mu_p = \mathbf{I}_p + \sum_{i=1}^{N} \Phi_p^{\mathrm{T}} \mathbf{N}_{ip}^{\mathrm{T}} \mathbf{M}_i \mathbf{N}_{ip} \Phi_p \tag{16d}$$

$$\upsilon_p = \Phi_p^{\mathrm{T}} \mathbf{M}_p + \sum_{i=1}^{N} \Phi_p^{\mathrm{T}} \mathbf{N}_{ip}^{\mathrm{T}} \mathbf{M}_i \tag{16e}$$

in which j is the imaginary unit. $\mathbf{H}_i(\omega)(i = 1, \ldots, N)$ and $\mathbf{H}_p(\omega)$ are the transfer functions of the suspension systems and megaframe in the component mode co-ordinate, respectively. The transfer functions in the total displacement co-ordinate $\mathbf{u}_t$ can be obtained from the result of Equations (13) and (14) according to the following co-ordinate transformation:

$$\mathbf{u}_t = \Gamma_t \mathbf{q}, \quad \Gamma_t = \begin{bmatrix} \Phi_1 & \mathbf{0} & \ldots & \mathbf{0} & \mathbf{N}_{1p}\Phi_p \\ \mathbf{0} & \Phi_2 & \ldots & \mathbf{0} & \mathbf{N}_{2p}\Phi_p \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \mathbf{0} & \mathbf{0} & \ldots & \Phi_N & \mathbf{N}_{Np}\Phi_p \\ \mathbf{0} & \mathbf{0} & \ldots & \mathbf{0} & \Phi_p \end{bmatrix} \tag{17}$$

However, it is in the modal co-ordinates that we can see the interaction between the suspension systems and megaframe more clearly. As can be seen in Equation (14), the influence of the megaframe on the suspension systems is that each of the suspension systems is input a dynamically amplified base acceleration by the megaframe, respectively. The second term of Equation (16d) describes the increment of the mass of the megaframe statically contributed by the suspension systems. The second term of Equation (16e) is the seismic force statically contributed by the suspension systems. The term $\sum_{i=1}^{N} \mathbf{Z}_i(\omega)\upsilon_i$ in Equation (15) is the driving forces dynamically transferred from the suspension systems, the term $-\omega^2 \sum_{i=1}^{N} \mathbf{Z}_i(\omega)\mu_i$ in Equation (15) is the dynamic stiffness contributed by the suspension systems.

Thus, the dynamic effect of the suspension systems to the megaframe is twofold. When the frequency of seismic force is tuned to the frequencies of the suspension systems, the suspension systems provide a large driving force and dynamic stiffness. The enlargement of the dynamic stiffness can reduce the vibration of the megaframe, which is the principle of TMD or MTMD. The principle and characteristics of TMD and MTMD have been widely discussed, but the driving effect of the secondary to the primary structure is less reminded or neglected in the previous study of TMD or MTMD. A recent study [6] shows that when the mass ratio of the secondary to the primary structure is large, the driving effect becomes a dominant effect in the dynamic behavior of the combined structure.

When the secondary systems have different natural frequencies, according to Equations (15) and (16a), the tuned driving forces of the secondary systems have different phases, thus the secondary structures asynchronously drive the primary system. The sum of the asynchronous driving forces is less than the sum of the synchronous driving forces, and the peak values of frequency response are distributed in a relatively wide range of frequency, this is called asynchronous driving principle. The following discussion will show how to use this basic principle in the vibration control of the combined system.

RESPONSE UNDER STATIONARY STOCHASTIC SEISMIC INPUT

A pseudo-excitation method [13] is used in dealing with seismic responses of the combined structure subjected to stationary stochastic seismic input. To find the response of the structure, the following steps are followed:

Step 1: In the range of the frequency discussed, J discrete frequency points $\omega_k (k = 1, \dots, J)$ are selected, for each point ω_k, the stationary stochastic seismic input is composed as follows:

$$\eta_{\mathrm{g}}(t) = \sqrt{S_g(\omega_k)}\, e^{\mathrm{j}\omega_k t} \tag{18}$$

in which $S_{\mathrm{g}}(\omega)$ is the Tajimi–Kanai-like filter zero mean white noise Gaussian process, the power spectral density function is expressed as follows:

$$S_{\mathrm{g}}(\omega) = \frac{\omega_{\mathrm{g}}^4 + (2\zeta_{\mathrm{g}}\omega_{\mathrm{g}}\omega)^2}{(\omega_{\mathrm{g}}^2 - \omega^2)^2 + (2\zeta_{\mathrm{g}}\omega_{\mathrm{g}}\omega)^2} S_0 \tag{19}$$

where ζ_{g}, ω_{g}, S_0 are some parameters of the model.

Step 2: Substituting Equation (18) in Equation (11), we obtain the following equation:

$$(-\omega_k^2 \mathbf{M}_q + \mathrm{j}\omega_k \mathbf{C}_q + \mathbf{K}_q)\{\mathbf{Q}_i(\omega_k)\} = -\mathbf{V}\sqrt{S_{\mathrm{g}}(\omega_k)} \tag{20}$$

in which $\mathbf{Q}_i(\omega_k)$ is the vector of the displacement magnitudes in the component mode co-ordinate. From Equation (17), the vector of the displacement magnitudes in the total co-ordinate in Equation (1) can be obtained as follows:

$$\{\mathbf{U}_{\mathrm{t}}(\omega_k)\} = \Gamma_{\mathrm{t}}\{\mathbf{Q}(\omega_k)\} \tag{21}$$

The displacement vector in the total co-ordinate can be expressed as follows:

$$\mathbf{u}_{\mathrm{t}}(\omega_k, t) = \Gamma_{\mathrm{t}}\{\mathbf{Q}(\omega_k)\}\, \mathrm{e}^{\mathrm{j}\omega_k t} \tag{22}$$

and its power spectral density is

$$\mathrm{S}_{uu}(\omega_k) = \{\mathbf{u}_{\mathrm{t}}\}^* \cdot \{\mathrm{u}_{\mathrm{t}}\} \tag{23}$$

where * means conjugate imaginary.

Step 3: Repeat steps 1 and 2 to obtain the power spectral density of all discrete points, then an interpolation function of power spectral density $\mathbf{S}_{uu}(\omega)$ of $\mathbf{u}_{\mathrm{t}}$ can be obtained. The mean square

response displacement is obtained as follows:

$$\sigma_u^2 = \int_{-\infty}^{+\infty} S_{uu}(\omega)\,\mathrm{d}\omega \tag{24}$$

OPTIMAL DESIGN METHOD

The numerical example is a MFSS of three megafloors, each of which is suspended with six secondary floors. The height of the each suspended floor is 3 m. The intensity of the equivalent distributed loads of the suspended floor is supposed to be 15 kN/m^2. The diameters of the four booms are designed to load the weight of the suspended floors with a safety coefficient of 1.2. The areas of the four columns of the megaframe are designed to load the weight above it with a safety coefficient of 1.5 on guard of the instability. The damping ratio is $\xi = 0.02$, the plane and the elevation are shown in Figures 1 and 2. A detailed dynamic analysis of such a system is presented in Reference [1].

The parameters in Equation (19) selected for analysis are $\zeta_g = 0.6$, $\omega_g = 5\pi$ rad/s, $S_0 = 1$ cm$^2/s^3$.

A recent study [14] shows that to variegate the diameters of the different suspension systems around the average magnitudes of all the diameters is the best way to differentiate the frequencies of the suspension systems. Suppose the diameter of the suspension system at the ith megafloor is arranged in the following sequence:

$$d_i = d_0[a + b(-0.5(N+1) + i)] \quad (i = 1, \ldots, N) \tag{25}$$

in which ad_0 is the average magnitude of all the diameters, bd_0 is the difference between two neighbouring suspension systems, Figures 3–5 show the mean square response displacement of

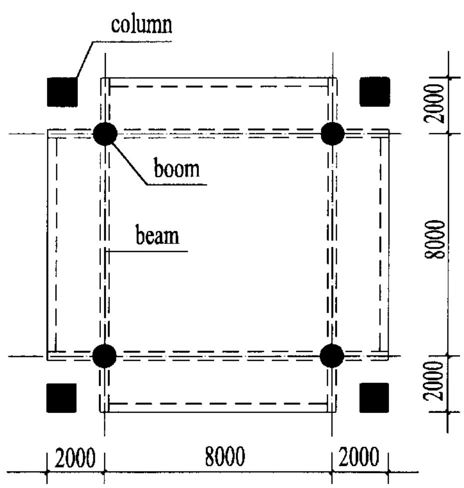

Figure 1. Plane.

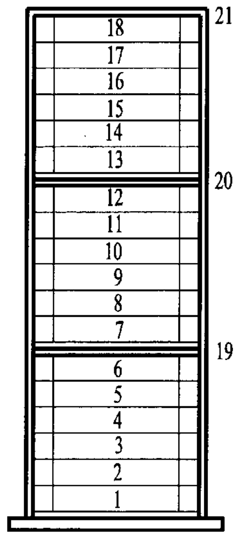

Figure 2. Elevation.

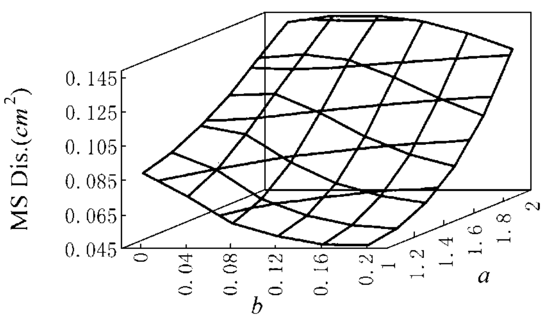

Figure 3. MS displacement of point 21.

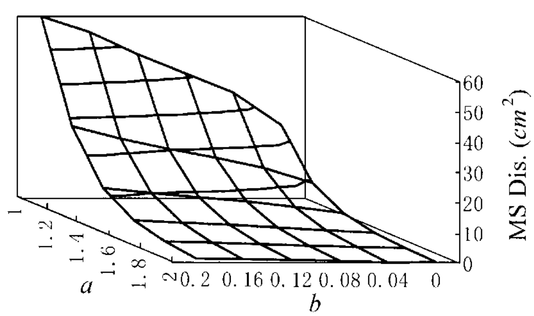

Figure 4. MS displacement of point 1.

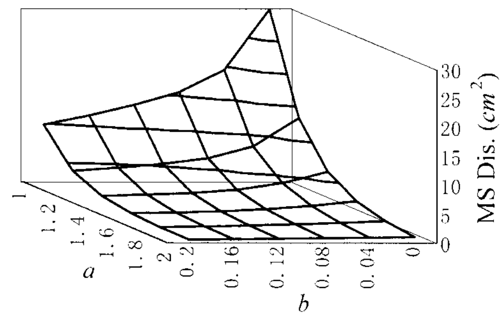

Figure 5. MS displacement of point 13.

the top megafloor (point 21), at the end of the suspension system of the lowest megafloor (point 1), and at the end of the suspension system of the top megafloor (point 13), respectively. With these figures, we have the following conclusions:

(1) The mean square response displacement (σ_{pN}^2) of the top megafloor decreases with the decreasing of a and the increasing of b.
(2) The mean square response displacement (σ_{sN}^2) at the end of the suspension system of the top megafloor decreases with the increasing of a and b.
(3) The mean square response displacement (σ_{s1}^2) at the end of the suspension system of the lowest megafloor decreases with the increasing of a and the decreasing of b.

The design of vibration control is to calculate values of a and b to obtain minimum response displacement, but from the above three conclusions we can see that the selection of the value of a and c is contradictory. Thus, we have to select a performance index to practice optimal design. The performance index reflects our desired performance. In the structure of MFSS, the desired effect of vibration control is to minimize the response displacement of the megafloor and to make the response displacement of the suspension systems acceptable. The megafloor, which is most important, to obtain high stiffness, is made of high strength concrete. The suspension systems, to be suspended, do not have problems such as instability or overturning; thus, some high strength and flexible steel frame, or cable can be used. Therefore, the deformation capacity of suspension systems can be much larger than that of the megaframe. As an example, an optimal vibration control problem is proposed as follows:

To calculate the value of a and b to minimize the following performance index:

$$\sigma_s(a, b) = (100\sigma_{pN}^2 + \sigma_{s1}^2 + \sigma_{sN}^2)^{1/2} \tag{26}$$

given a and b subjected to the following constraints:

$$1.0 \leqslant a \leqslant 2.0 \quad \text{and} \quad 0.0 \leqslant b \leqslant 0.2 \tag{27}$$

In this optimal problem, the result is $a = 1.4$ and $b = 0.12$. This is proposed as the best effect of vibration control available. If the result still cannot meet the design requirement, what is left is to increase the lateral stiffness of the megaframe and the suspended frame proportionally, and then repeat the above vibration control problem.

THE EFFECT OF THE VIBRATION CONTROL

The above optimal design problem is based on the zero mean stationary white noise input. From Figure 3, we can see that the response displacement of the top megafloor can be decreased by about 20 per cent when applying the vibration control of asynchronous driving principle.

A recent study [14] presents a method to study the non-stationary stochastic analysis of the MFSS. This method is employed in this paper to illustrate the effectiveness of the vibration control in a more common sense. The parameter of the MFSS is the same as the one discussed above, the only difference is that in Equation (11), the seismic input is defined as Tajimi–Kanai-like filter. This process can be written as follows:

$$\eta_g(t) = -\omega_g^2 u_g(t) - 2\zeta_g \omega_g \dot{u}_g(t) \tag{28}$$

where u_g and $\dot{u}_g$ are the solution of a differential equation of a single oscillator subjected to a non-stationary white noise input, i.e.

$$\ddot{u}_g + 2\zeta_g \omega_g \dot{u}_g + \omega_g^2 u_g = -\varphi(t)\xi(t) \tag{29}$$

in which ζ_g and ω_g are two parameters which define the characteristics of the filter, φ(t) is a deterministic shape function and $\zeta(t)$ is a zero mean Gaussian white noise process with a one-sided power spectral density S_0. The parameters are selected as $\zeta_g = 0.6$, $\omega_g = 5\pi$ rad/s, $S_0 = 1$ cm^2/s$^3 \cdot \varphi(t)$ is chosen as Geto model:

$$\varphi(t) = g\frac{t}{t_g}\exp\left(1 - \frac{t}{t_g}\right) \tag{30}$$

in which $g = 1$ and $t_g = 5$ sec, t_g is the time when the function reaches its peak value.

The values of a and b are taken as the above optimal result. Figure 6 shows the mean square response displacement of the megaframe with and without the vibration control. Figure 7 shows the mean square response displacement of the suspension systems with and without the vibration control. From the figures, we can see that the vibration control is effective. Not only the response of the megaframe decreases, it also redistributes the lateral stiffness of the suspension systems.

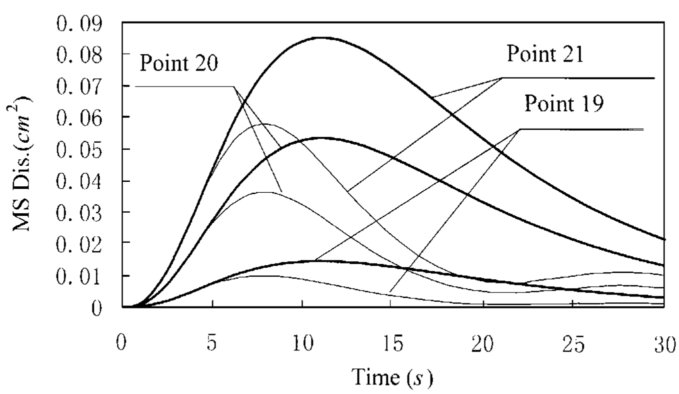

Figure 6. MS displacement of the megaframe with (thin solid line) and without (thick solid line) the vibration control.

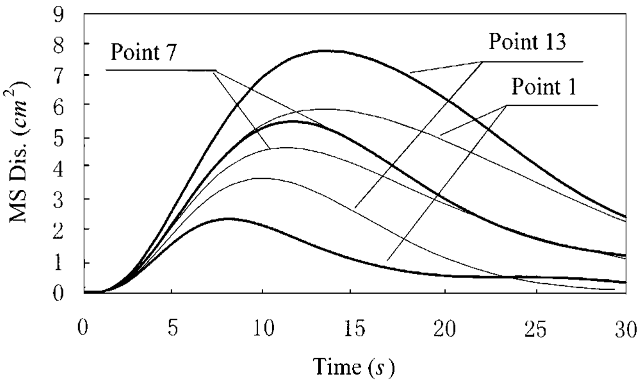

Figure 7. MS displacement of the suspension systems with (thin solid line) and without (thick solid line) the vibration control.

Consequently, the suspension systems at upper megafloors have larger stiffness than those at the lower megafloors. This is not only advantageous to earthquake resistance, but also advantageous to wind resistance, because wind force has greater intensity with the increase in the height of the building. Consequently, the dynamic responses of the suspension systems are evenly distributed along with the height of the megaframe. This is also an important result of the vibration control with asynchronous driving principle. In fact, a performance index reflecting the use of this result is selected in the damping control of the MFSS [14].

CONCLUSIONS

MFSS is a kind of new structural system with good seismic capacity. The dynamic property of the structure depends on the interaction of the primary and secondary structures of the combined structure. The driving force of suspension systems to the megaframe is the main dynamic impetus of the MFSS. When the frequencies of the suspension systems are differentiated, the suspension systems drive the megaframe asynchronously, which can reduce the vibration of the megaframe effectively and make the response of the suspension systems well distributed. A vibration control method according to this principle is presented. The simulation results show that the vibration control method is effective for both the megaframe and suspension systems.

Although the study in this paper is based on the MFSS, but the insightful depiction of the interaction between the primary and secondary structure is of common sense. Therefore, the vibration control of asynchronous driving principle can be applied to some other combined structures with large secondary to primary mass ratio.

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